WORKING PAPER

CHANGES IN NONPOINT NUTRIENT LOADING INTO EUROPEAN FRESHWATERS: TRENDS AND CONSEQUENCES SINCE 1950 AND NOT-IMPOSSIBLE CHANGES UNTIL 2080

Horst Behrendt

April 1988
WP-88-026

IIASA
International Institute
for Applied Systems Analysis

CHANGES IN NONPOINT NUTRIENT LOADING INTO EUROPEAN FRESHWATERS: TRENDS AND CONSEQUENCES SINCE 1950 AND NOT-IMPOSSIBLE CHANGES UNTIL 2080

Horst Behrendt

April 1988
WP-88-026

Participant in the 1987 YSSP. Current affiliation is Institute of Sciences of the G.D.R., Academy of Sciences.

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

Foreword

Devising strategies that foster long-term economic development in Europe within a framework of ecological sustainability is the major theme of IIASA's study: The Future Environments for Europe: Some Implications of Alternative Development Paths. This Working Paper is a direct contribution to that study.

There have been many reports in the environmental literature linking agricultural activities to ecological degradation. Few of them, however, have a time horizon of decades to a century. When viewed over such a time span, ecological alterations, that may currently appear to be minor in the short term, may cause major environmental effects due to the accumulation of small changes over many years. From a policy point of view, such effects are important for two reasons. Firstly, they may come as a "surprise" to governments and the public alike. Secondly, once the major change is observed, it may be too late to develop an appropriate management strategy to minimize much of the damage. (The sudden advent of Waldsterben in Central Europe in the early 1980's is a recent example.) From a scientific point of view, such effects are of interest because they exemplify how changes, occurring on relatively slow time scales, can trigger sudden threshold responses in the environment.

This paper has been written by H. Behrendt of the Institute of Geography and Geoecology, Academy of Sciences of the German Democratic Republic. Mr. Behrendt was an IIASA YSSPer during the summer of 1987.

W.M. Stigliani
Study Manager
Future Environments for Europe

TABLE OF CONTENTS:

CHANGES IN NONPOINT NUTRIENT LOADING INTO EUROPEAN FRESHWATERS: TRENDS AND CONSEQUENCES SINCE 1950 AND NOT-IMPOSSIBLE CHANGES UNTIL 2080

Horst Behrendt

SUMMARY

An analysis of changes since the 1940s in nonpoint nutrient loadings into aquatic ecosystems was performed for four Central European countries. The work was based largely on statistics of agricultural production. As part of the study on the Future Environments for Europe: Some Implications of Alternative Development Paths (STIGLIANI et al, 1987), the goal was to contribute to the understanding of major changes in the European environment that might result from natural environmental variations or from human activities.

Trends for nutrient loading in the past were estimated and not-impossible future changes were considered for a time scale of one hundred years.

Input-output analysis and mass balances of nutrients were used for the investigation.

A continuation of the current agricultural practice might lead, not only to high rates of nitrate leaching, but also to a real risk of phosphorus leaching in the time scale considered. Soils with low phosphorus sorption capacities and a high water table are especially vulnerable if the current phosphorus application practices in agricultural areas continue.

A method for determination of nitrogen fixation is proposed based on an input-output analysis of the agricultural nitrogen cycle.

General features of the connections between nutrient inputs to and nutrient losses from agricultural areas were derived. On this basis, it seems possible to quantify the effects of different strategies of agricultural development regarding their influences on the different environments and nutrient loadings.

A comparison of different strategies shows that only a better nutrient utilization guarantees decreasing nutrient losses to soils and waters in the future.

In the case of nitrogen, an increase in nitrogen fixation or in denitrification, especially based on new biotechnologies, might reduce nitrogen leaching, but a substantial improvement in our knowledge of all the processes controlling the nitrogen cycle is needed.

The systems analysis approach as well as the statistical databases used permit the realization of similar analyses regarding other relevant materials or elements with minimal additional effort.

1. INTRODUCTION

Currently the biogeochemical cycles of two essential nutrients - nitrogen and phosphorus - are strongly influenced by human activities. The highest use of these nutrients in the world is concentrated on the European continent.

The input from artificial fertilizers of nitrogen and phosphorus to European agriculture in 1982 was approximately 15 million tons of N and 3.5 million tons of P, (FAO statistics 1985). The influence of man on the nitrogen and phosphorus cycles has changed drastically in the last four decades. In comparison to the fifties, the agricultural demand of nutrients has increased more than threefold.

Environmental consequences of these changes are manifold and serious. In general, many effects on the environment, especially on the water resources, are known. However, with regard to general trends for the continent as a whole, the composition of nutrient loads and, in particular, their rates of change have so far not been subject to thorough investigation.

Nutrient loadings into freshwaters and coastal waters from point and nonpoint sources have increased during the last decades. This has resulted in eutrophication of lakes, rivers and seas (especially the North Sea and the Baltic Sea), contamination of ground and drinking waters, health risks and other impacts. Above all, the eutrophication of the North and the Baltic Sea, as shown by ANONYMOUS (1987), BABENERD and ZEITZSCHEL (1985), LARSSON et al (1985) and NEHRING (1985), show the international scale of the nutrient loading problem. Therefore predictions of nutrient loadings are necessary in order to make well-informed decisions for dealing with these problems. This requires understanding the current situation, long-term changes of loading and long-term behavior of aquatic ecosystems. Long-term measurements only exist in a few cases, and a generalization of these measurements to larger regions, countries or the continent as a whole is not possible. Additionally, the connection between these measurements and general relevant parameters of human development is necessary.

2. MATERIAL AND METHODS

The analysis and future prediction of the freshwater nutrient loading for a certain region is based on:

- the analysis of changes in the relevant and available parameters describing human development,
- the analysis of changes in loadings from different nutrient sources on the basis of models including the parameters mentioned above as input,
- the analysis of the present situation and regional differences, and;
- the analysis of additional parameters influencing the nutrient loading indirectly.

These analyses form the basis for identification of the main future sources and areas of nutrient pollution, and thus may assist decision makers. The investigations were concentrated on the analysis of 4 different countries in the European continent, Denmark, Germany, F.R., G.D.R. and The Netherlands. Due to their close location, there are no big differences in climatic conditions, which could influence the analysis. The method established here could also be extended to other countries and regions of Europe.

Statistics on the development of agricultural production were the main data base. In most cases the statistical yearbooks were sufficient for getting the necessary information. In cases where statistical yearbooks were insufficient, other statistics (FAO or EC) were used as a supplementary source. The main difficulty was the estimation of greenfodder yield for The Netherlands. In years without data on greenfodder yield, the correlation between greenfodder yield and total crops was used to estimate it (including maize).

The main methods adopted were the calculation of material balances, and input-output analyses. Data for the quantification of the different processes were taken from the literature with the exception of the processes connected with nutrient loading. Estimates for the loading were obtained from the mass balance calculations, from which their changes and trends were compared with measured data.

3. NONPOINT SOURCES OF (FRESHWATER) NUTRIENT LOADING

The magnitude of nutrient loadings from nonpoint sources into aquatic ecosystems, as well as their changes over time depend on various factors. Firstly, the behavior of the nutrient itself in different ecosystems and its different chemical forms affect the losses. Secondly, geological, geochemical, geophysical and hydrological factors differing from watershed to watershed strongly influence the flux of nutrients from terrestrial to aquatic ecosystems.

Furthermore, the significance of the loading is dependent on human activities giving rise to the loading directly, but also on more general parameters, characterizing the development and the state of a region; e.g., population density, consumptive behavior, industrial production, and the efficiency of wastewater treatment. In all European countries, improvements in waste water treatment in the last decade have resulted in a leveling off or even in a drastic reduction in point source loading (for example in Sweden and Finland).

Compared to point sources, information about nonpoint sources and treatment methods is rather sparse. In most countries, nonpoint or diffuse nutrient loading was not recognized as a problem until the late 1960s. Only in the last decade has it been realized that the reduction of wastewater inputs may not solve the eutrophication problem. Nonpoint sources may account for more than 50% of the total nutrient load (VOLLENWEIDER, 1974, NOVOTNY and CHESTERS, 1981). In many areas, nonpoint sources, such as runoff from cropland and urban runoff, are becoming more and more a dominant pollution problem.

Therefore, this paper investigates the historical changes in nonpoint nutrient loadings, their connections to important development activities (for example, agriculture) and the "not-impossible" changes in these sources that might occur in the future.

The main sources of nonpoint nutrient loading are the output processes from the different terrestrial ecosystems, especially agricultural, forested and urban areas, as well as nutrient deposition from the atmosphere. This paper mainly focuses on nutrient loading from agricultural and forested ecosystems.

3.1 Nutrient inputs from the atmosphere

3.1.1. Phosphorus

Data on the atmospheric part of the phosphorus cycle, and especially on the phosphorus deposition, are scarce. The main sources of atmospheric phosphorus are believed to be high temperature combustion of organic matter, dust from terrestrial areas, and seaspray. PIERROU (1976) estimated the global input of phosphorus to the atmosphere caused by burning of coal and oil to be about 0,08 Tg P/yr. Estimates for the other two sources are not available, but comparison of the value from combustion to the calculated global fallout (dry and wet deposition) indicates that P-inputs by sea-spray and dust must be about two orders of magnitude higher than annual input due to combustion.

The P-concentrations in rain water measured by different authors vary from less than 0.002 mg TP/l (TP - total phosphorus) for rural areas to more than 1.1 mg TP/l for industrialized or urban regions (RIGLER, 1974, NOVOTNY and CHESTERS, 1981). Data on P-deposition rates have been published by AHL (1979), BERNHARDT (1978), RIGLER (1974) and WAGNER and WOHLAND (1976). They vary as much as the P-concentrations in rain water, the average being between 0.2 and 0.7 kg P/ ha yr. WAGNER and WOHLAND (1976) estimated the changes in phosphorus deposition with time. On this basis it can be assumed that the P-deposition rate of the Bodensee region has increased between 1963/64 and 1973/74 more than fivefold.

Because dust is one of the main sources for phosphorus in the atmosphere, it can be assumed that the phosphorus deposition rate depends on dust emissions caused by human activities. In contrast to the results of WAGNER and WOHLAND (1976), statistics on dust emissions show a continuous decrease since 1966 (Statistical yearbook of Germany, F.R. 1986). Due to the present ignorance on sources of phosphorus in the atmosphere and their historical trends, it is very difficult to estimate future phosphorus deposition.

However, on the basis of existing data, the following assumptions on P deposition were made:

- After the Second World War the P-deposition was about 0.2 Kg P/ha yr and increased linearly with time until the mid 1970s, when it reached an average value of 0.5 kg/ha yr in large regions of Central Europe.
- Since the end of the 1970s the deposition rate has remained almost constant and will decrease slowly in the next decades.

These assumptions form a basis for modeling of the P-cycle in agricultural and forested ecosystems, and the direct loading of freshwater from the atmosphere.

3.1.2. Nitrogen

The atmospheric part of the nitrogen cycle has been investigated in more detail than that of phosphorus, especially in connection with the problem of acidic deposition.

Data exist on current and past emissions of ammonia/ammonium and nitrogen oxides. Statistical yearbooks of Germany, F.R. and The Netherlands include statistics on the emissions of nitrogen oxides (calculated as nitrite) for the main sources for the period of 1966 to 1985. ASMAN (1986) quantified the sources of ammonia emissions for the whole continent in 1982. On the basis of his assumptions, historical changes of ammonia emissions can be estimated. Many authors have investigated the nitrogen deposition and its consequences in different regions of Europe with special emphasis on acidification and "Waldsterben". Time series for ammonia and nitrate wet fall-out were published by JORGENSEN (1979) (cited by SCHRÖDER, 1985) for Denmark. Changes of nitrate deposition at some experimental stations of England were shown by GOULDING et al (1986). An overview on the changes of nitrogen deposition in Scandinavian forests during the last hundred years was given by ANDERSEN (1987).

From all this material, it can be concluded that nitrogen deposition varies greatly from region to region, but in most cases it has strongly increased (doubled or tripled) since the end of the 1950s. The main sources for nitrogen in the atmosphere are the volatilization of ammonia from animal excreta, other organic material and nitrogen fertilizers (see BUIJSMAN et al, 1985), and from combustion sources (cars, industries, and power plants).

The atmospheric nitrogen input to terrestrial and aquatic ecosystems was calculated for each country on the basis of livestock and fertilizer consumption statistics and published data on nitrogen oxide emissions. The specific ammonia emission factors published by BUIJSMAN et al (1985) were used. Nitrogen deposition rates were recalculated from the total emissions by means of the results of the ammonia transport model of ASMAN (1986). For Denmark and G.D.R., data on nitrogen oxide emissions were not available. It was assumed that Denmark has approximately the same specific nitrogen oxides deposition rates as The Netherlands. In G.D.R., more than 80% of the cars use single stroke engines, and brown coal is the major fuel for industry and electricity production. Both of these sources produce relatively low nitrogen oxide emissions. Therefore, it was assumed that the nitrogen oxide emissions of the G.D.R. were less than 50% of those in Germany, F.R., but that the historical trends past have been parallel.

For Central Europe the current annual nitrogen deposition is estimated to vary between 30 and 50 kg N/ha. About 50 % of this is deposited as ammonia or ammonium originating from agricultural sources. In the 1950s the nitrogen deposition amounted to 15-20 kg N/ha i.e., less than 50 % of the present deposition. Assuming that the wet deposition accounts for approximately 50 % of the total nitrogen deposition (dry and wet deposition), the estimates agree with measured nitrogen deposition rates (see STEWART et al., 1983, SCHRÖDER, 1985, BABENERD and ZEITSCHEL, 1986 and ANDERSEN, 1987).

3.2. Nutrient loading from agricultural areas

Among human activities, agriculture is the main consumer of nutrients. Especially after the Second World War, the demand for chemical fertilizers has grown rapidly in connection with the increase of agricultural production. Overviews of the development of agricultural fertilizer consumption for different countries and for the whole world have been given by various authors (for example see KONPLAN DIKS et al, 1985; STEWART et al, 1983; PANNIKOW and MINEJEW, 1980 and BERNHARDT, 1978). The largest increase in fertilizer use has occurred in Europe. The development with time shows similarities in different countries. Firstly, a strong increase in phosphorus fertilizer use occurred in the late 1950s and early 1960s. In the 1970s the consumption of P-fertilizer remained constant followed by a slight decrease. The development of nitrogen fertilizer use differs from that of phosphorus in that there has been a continuing growth in the 1970s. Only in the 1980s can a leveling-off be observed. Generally, it has to be noted that the consumption of chemical fertilizers has increased more strongly than agricultural production has increased. The consequences are well known, particularly in the case of nitrogen. The loadings into waterbodies have reached such high levels that nitrogen concentrations in drinking waters in many parts of Europe pose a risk for human health. Also, other nutrient inputs to agricultural areas, such as manure application and nutrient deposition from the atmosphere have increased more or less continuously in the last 40 years.

In the following, trends and quantities of nonpoint nutrient loadings caused by agricultural development are estimated using generally available statistical data. The first step in the analysis is the estimation of the nutrient mass balances for each country (expressed per hectar of agricultural area).

As a first approximation, the nutrient losses to the different environmental reservoirs (soil, water, atmosphere) were assumed to be equal to the differences between all nutrient inputs to and outputs from crops from this area,

$$\Sigma\ (\ LOSSES\ ) = \Sigma\ (\ INPUTS\ -\ OUTPUT_{CROPS})$$

Statistical yearbooks between 1949 and 1986 for the 4 countries (Denmark, Germany, F.R., G.D.R. and The Netherlands) were used to estimate the fertilizer consumption and nutrient inputs by manure application on the one hand, and outputs by crops on the other. The calculation of nutrient inputs by manure was carried out on the basis of the livestock data (cattle, pigs, sheep and poultry) multiplied by the specific nutrient amount excreted per animal and year. The nutrient output by crops was calculated based on the yield of different crops and their specific nutrient content. It was assumed that the specific nutrient amount per animal as well as the specific nutrient content of plants are the same in the different countries and have not been changed with time. The specific values used for animals and plants are given in Tables 1 and 2. They are mean values from different published sources (BERNHARDT,1978; STEWART et al, 1983; LAWA,1982; PANNIKOV and MINEJEW,1980; HAMM,1976 and BOSSHART, 1985). A reduction was assumed for nitrogen by emission factors of ammonia presented by BUIJSMAN et al. (1985).

The calculated values of nutrient inputs due to manure application are comparable with published data (see Statistical Yearbook of The Netherlands, 1980, 1983 and 1986).

3.2.1. The phosphorus cycle in agriculture and its consequences

3.2.1.1. Input - output analysis

The main processes of the agricultural phosphorus cycle are shown in Figure 1.

Table 1 Specific annual amounts of nutrients excreted by different animals.

	Cattle	Pigs	Sheep	Poultry
specific Phosphorus amount [Kg P/(animal yr)]	12.2	2.3	1.1	0.23
specific Nitrogen amount [Kg N/(animal yr)]	46.0	10.8	8.9	0.22

Table 2: Specific nutrient contents of different agricultural plants

plant	spec. P-content [g P/Kg]	spec. N-content [g N/Kg]
Cereals	4.8	28
Legumes	7.6	60
Oil-fruits	12.0	55
Potatoes	0.8	5
Sugar beets	0.8	5
Fodder beets	0.45	3
Greenfodder	3.0	18
Vegetables	1.2	6

Phosphorus inputs into agricultural areas by seeds and sewage or wastewater sludge are not considered in the following analysis, because these inputs are small in comparison to the other inputs. In general, the nutrient content of sewage and waste water sludge is comparable with that of fertilizers (further see Section 3.), but as a source of phosphorus they amount to only about 10 % of fertilizer consumption.

The input - output analysis (without deposition) is presented for two countries (Germany, F.R., and The Netherlands) in Figures 2 and 3. The analysis assumes that all the phosphorus from manure and fertilizer was applied evenly on the total agricultural area. This is a very crude simplification, but data bases and time were insufficient for a detailed regional analysis. In all countries a continuous growth of phosphorus inputs by manure and fertilizers until the year 1980 was recorded by increasing fertilizer consumption, as well as increasing amounts of live-stock. Since 1980, the P-inputs to agriculture have decreased in Denmark, Germany, F.R. and G.D.R. caused by reductions of fertilizer application. Compared to the phosphorus inputs, the increase in P-outputs is smaller and shows more annual variation due to the strong dependence of agricultural yields on meteorological conditions.

The difference between input and output is determined more by inputs than by outputs. This difference can roughly be interpreted as the amount of phosphorus accumulating in the soil each year, because, in general, the losses of phosphorus into water courses are very small compared to the difference (an overview on measured P-loading rates from

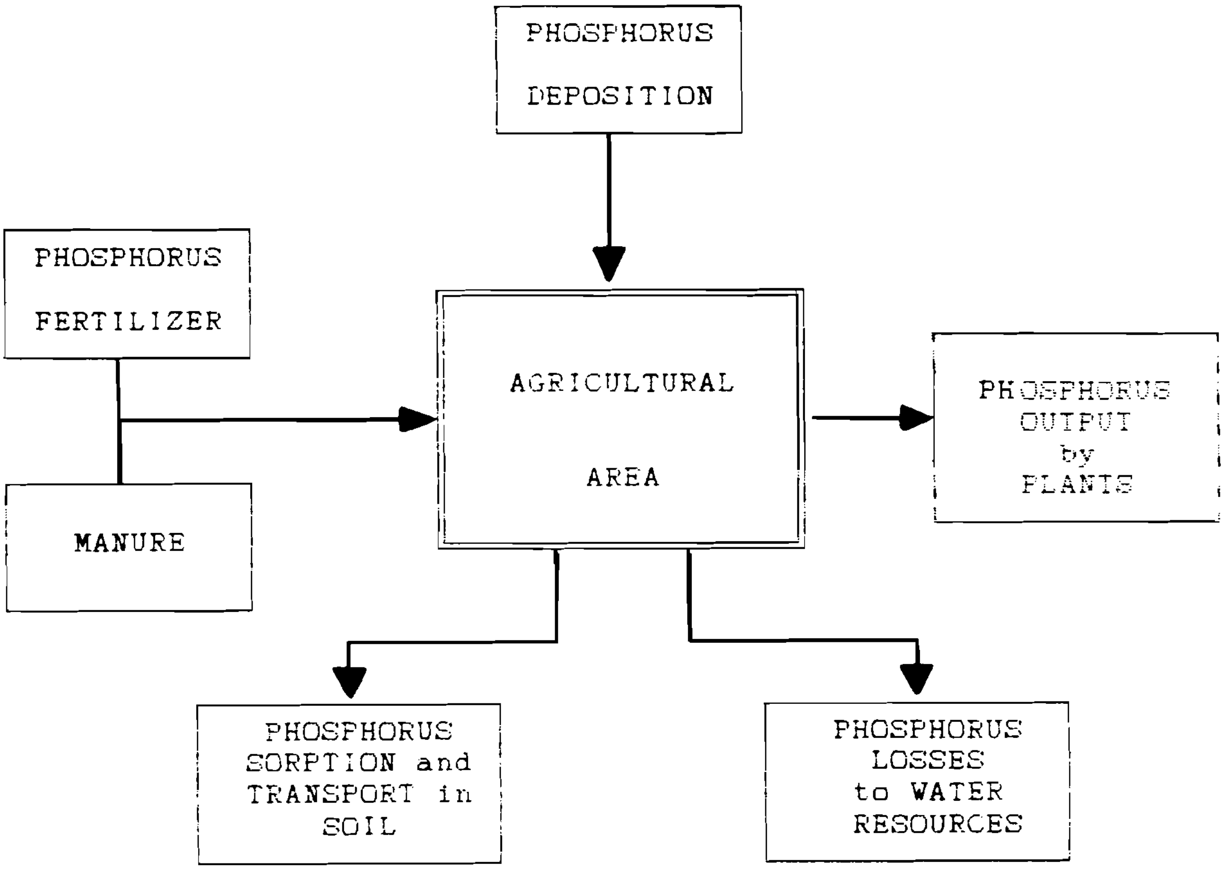

Figure 1: Main processes determining the phosphorus cycle in agricultural areas.

different areas is given in Table 3). That means that at present 20 - 45 Kg P/ha is accumulating annually in the soil depending on the P-input.

In general the utilization rate of phosphorus inputs has decreased until very recently. This current trend of increasing phosphorus utilization is caused not only by reduction of P-inputs, but also by favorable meteorological conditions.

Figure 4 presents the relationship between the phosphorus inputs and the output by crops, and the differences of both, respectively. The relationships are similar for all investigated countries, resulting in high correlations.

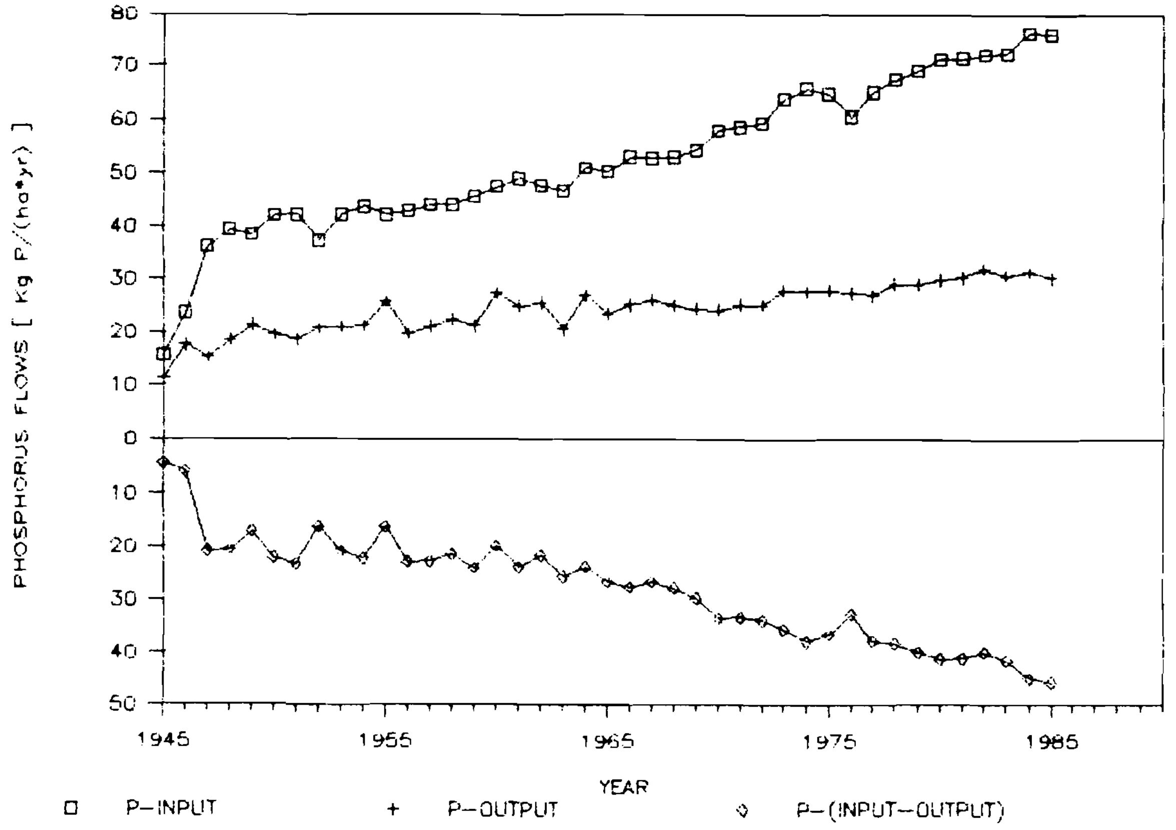

Figure 2: Estimated development of phosphorus input by fertilizers and manure, of phosphorus output by crops and of the difference between input and output for The Netherlands from 1945 to 1985.

Because the phosphorus deposition rate is low in comparison to the amount of fertilizers and manure applied (< 1 %), these relationships do not change significantly when including this input.

3.2.1.2. Phosphorus loss processes

Since the input-output analysis showed that a significant fraction of the phosphorus inputs in agricultural areas remains unused, it is important from the environmental point of view to determine the rate of accumulation of this unused phosphorus. In the case of phosphorus, direct losses to the atmosphere can be neglected, and the measured losses into freshwater and/or groundwater are small in comparison to the residual phosphorus retained in agricultural areas. An average value of about 0.5 KgP/ (ha yr) may be assumed

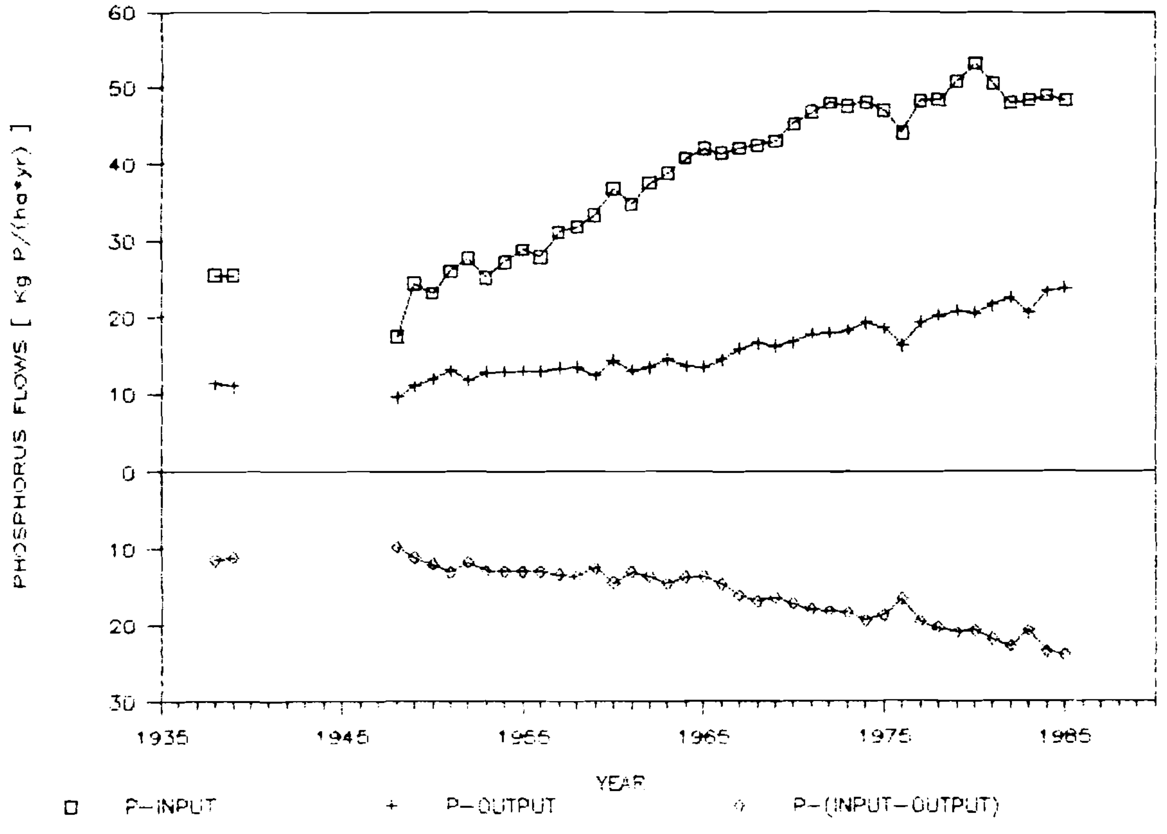

Figure 3: Estimated development of phosphorus input by fertilizer and manure, of phosphorus output by crops and of the difference between input and output for Germany, F.R. from 1938 to 1985.

as the direct phosphorus loading from agricultural areas (HAMM, 1976, VOLLENWEIDER and DILLON, 1978, BERNHARDT, 1978 and LAWA, 1982). For natural areas and forest this loading is lower (HAMM, 1976; VOLLENWEIDER and DILLON, 1978; AHL, 1979 and FIEDLER et al., 1985). A quantitative connection between the phosphorus input and the phosphorus loading must exist, but it has not yet been evaluated in the literature. It is assumed in this paper that currently, the main part of the unused phosphorus in agriculture remains in the soil.

Consequently, the next questions are, what happens to the phosphorus in the soil, and how can this phosphorus influence other processes? First of all, it can be assumed, that transport processes of phosphorus in soil are slow due to the absorption of P onto soil particles, and to a first approximation, can be neglected. This implies that the phosphorus content of the upper soil layer has increased. The magnitude of this change depends on

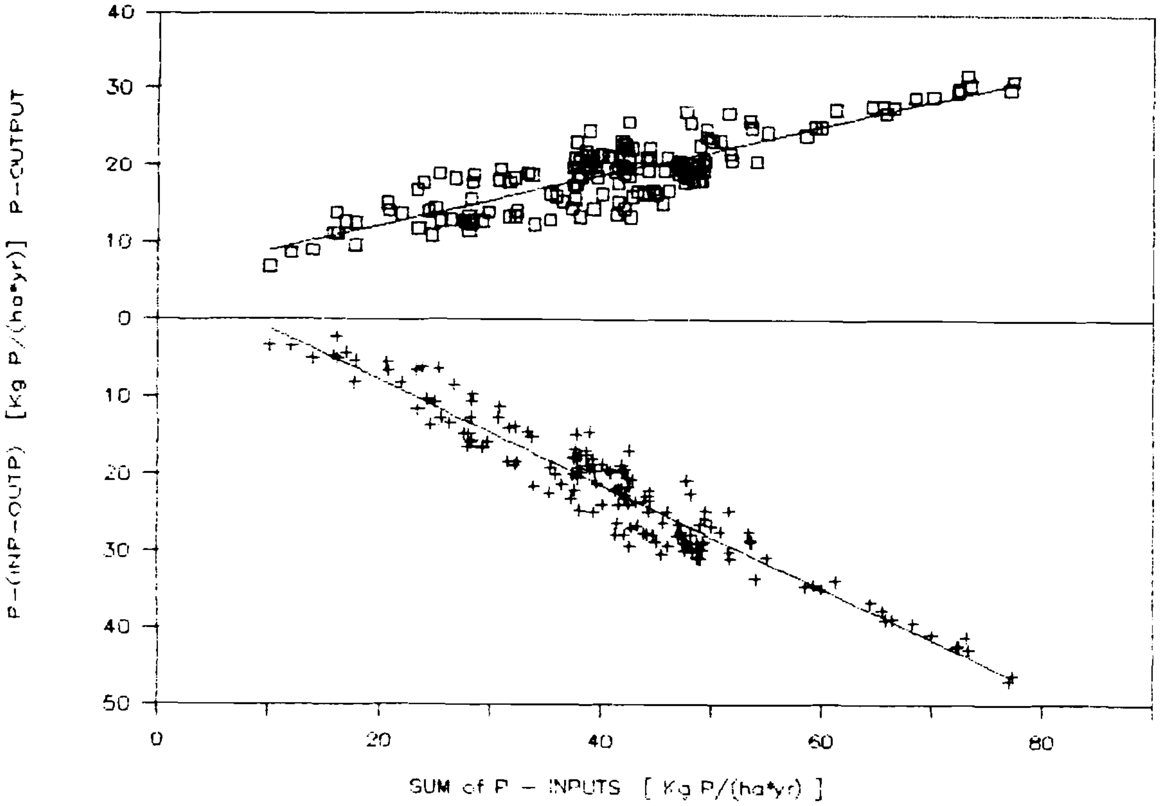

Figure 4: Relationship between the phosphorus input by fertilizers and manure and phosphorus output by crops, and the differences of both processes in the agricultural areas of Denmark, Germany F.R., G.D.R., and The Netherlands over the time period 1945-1985 (n = 156). Regression equations: P - OUTPUT = 5.831 + 0.324 * P - INPUT; r^2=0.74; P - (INP-OUTPUT) = -5.831 + 0.676 * P - INPUT; r^2=0.925.

the accumulated phosphorus per year. Table 3 gives an overview on the range of soil P-content based on different studies.

For further calculations, a phosphorus content of 0.08 % or 1600 kg P/ha in the upper 0.2 m of natural soils is assumed. The calculated 40-year accumulation of phosphorus in the soil varies between 600 (Denmark) and 1150 (The Netherlands) kg P/ha. That means that the phosphorus content of soils has increased in this period by 40 to 85 % .

Measurements of the soil P-content confirm these calculations. Statistics on the state of the phosphorus supply of agricultural areas in G.D.R., given by RUNGE and MATZEL (1985), verify an increasing proportion of soils with high P-contents and a large decrease in soils with low P-content during the last twenty years.

Table 3: Total amount of soil phosphorus in the upper 0.2 meter of the soil profile according to different authors

Author	Specific P-content of the soil [%]	P-content per area (*) [kg P / ha]
WAZER (1961)	0.1 - 0.12	2000 - 2400
ERNST and van DAMME (1983)	0.08	1600
LAWA (1982)	0.015 - 0.15	300 - 3000
PANNIKOV and MINEJEW (1980)	0.05 - 0.10	1000 - 2000

(*) - calculated on the basis of an arbitrary value of soil density of 1 kg $dm-^3$.

Dutch investigations on soil P-sorption capacities show the same tendency. BREEUWSMA and SCHOUMANS (1987a,b) pointed out that in The Netherlands the capacity of the soil to sorb phosphate has already been exhausted at a few locations where soils have become saturated by phosphate.

Assuming that the current trends continue, the phosphorus content of agricultural soils will increase in the next one hundred years by 150 % to 300 % i.e., between 4000 and 6000 kg P/ha. Such high values would clearly exceed the normal range of phosphorus saturation in the upper soil layers.

Considering the transport of phosphorus in the soil, two processes have to be discussed, the horizontal transport, mainly by erosion, and the vertical transport by leaching due to phosphorus saturation of the upper soil layers. Both processes are important for the phosphorus loading into fresh and groundwaters.

Phosphorus loading caused by erosion depends on:

- phosphorus content of the soil
- vegetation cover
- slope
- soil structure
- amount and frequency of precipitation.

It can be assumed, as a first approximation, that all the factors, except the phosphorus content of the soil, remain constant in the future. This implies that phosphorus loading by erosion will increase in parallel to the increase in the phosphorus content of the soil. That would mean that the phosphorus loading of freshwater caused by erosion which has increased in the last forty years by 40 to 85 %, will increase in the next hundred years by 150 to 300 %. Figure 5 presents the estimated changes of the soil P-content in the past and the not-impossible changes in the future for the four countries investigated. The trend of the phosphorus loading by erosion may be assumed as approximately the same or even stronger, taking into account the preferential selectivity of erosion for fine soil particles (clay, silt), onto which the phosphorus is mainly adsorbed.

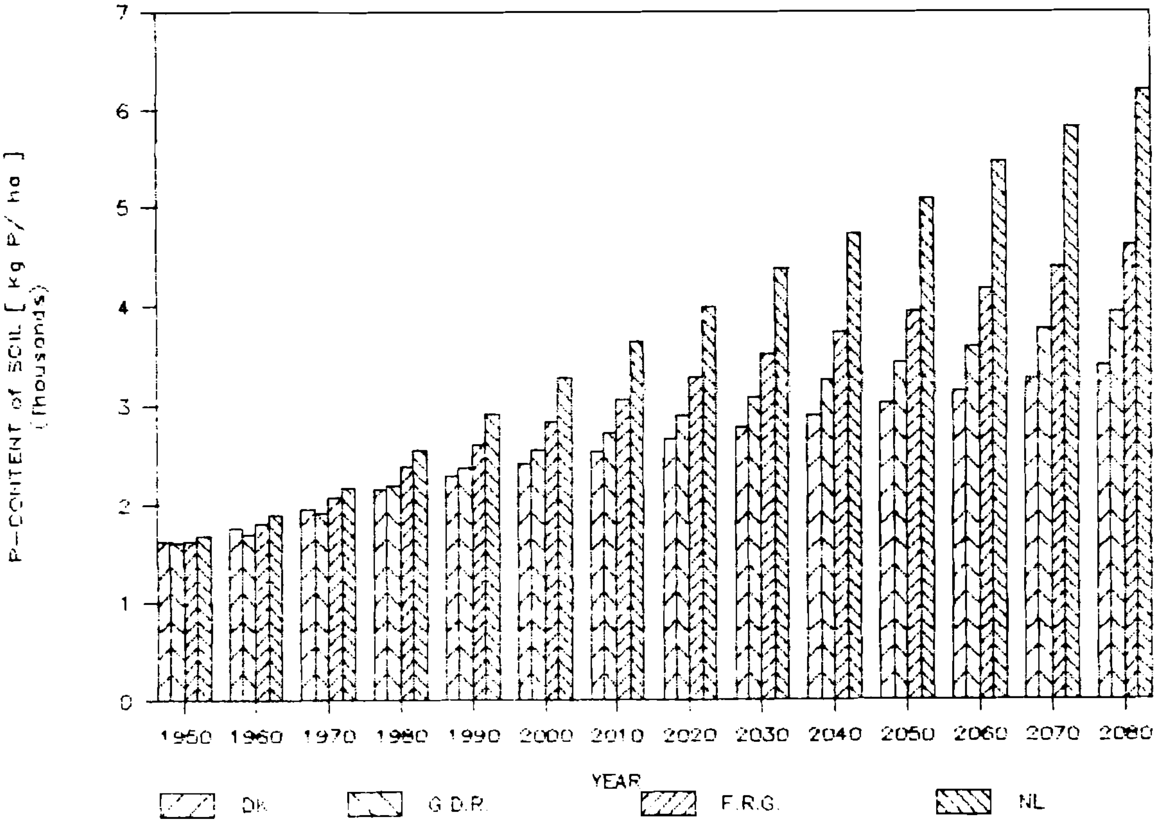

Figure 5 Changes of the phosphorus content in the soil since 1950 and expected for the next one hundred years for the four countries investigated. Estimations are based on annual phosphorus accumulation in the soil. For changes in the future the same rate of applications are assumed as for the period between 1980 and 1985. In 1950 phosphorus content of soil was assumed as 1600 kg P/ ha for all four countries.

Because some of the other parameters listed above have changed in the past as well, due to an increase in the mean size of agricultural fields caused by concentration of production, and a higher level of mechanization, the effect of erosion in the past has probably been even greater than the percent increase in phosphorus content in the soil. The same applies to future development, if no measures are taken against erosion. Nevertheless, only a small fraction of the phosphorus transported by erosion reaches the watercourses. It is also mostly insoluble, but may, under conditions that favor desorption, be transformed into water-soluble phosphorus, which is available for uptake by algae, causing subsequent eutrophication.

However, the highest risk of increased phosphorus loading stems from the limited phosphorus sorption capacities of soils. If the current practice of overfertilization continues, the phosphorus saturation of the upper soil will cause leaching to deeper soil layers. There is a positive feed-back with respect to leaching because the phosphorus sorption capacity decreases with decreasing redox-potential, and the redox-potential decreases with increasing soil depth. However, currently a substantial lack of knowledge and observed data exists in this special field.

It can be assumed that the generally higher phosphate concentrations in drainage waters compared to natural springs (DRIESCHER pers.com.) are indicative of this phenomenon.

Also, measurements of the phosphorus content in soil profiles show an increase of phosphorus concentration in the upper and deeper layers of agricultural soils. (See for example ERNST and van DAMME, 1983, PANNIKOV and MINEJEW, 1980).

Recently, Dutch researchers have described this problem in more detail (BREEUWSMA and SCHOUMANS, 1987 a, SCHOUMANS et al, 1987 and BREEUWSMA and SCHOUMANS, 1987 b). In these studies soil data were used to assess the total phosphate sorption capacity of the soil. Long-term effects on soils of different manure application scenarios were simulated, using a regional model. The conclusions authors were:

- High application rates of manure in areas of intensive livestock production may eventually cause phosphate leaching to ground and surface waters.
- At some locations the soil has become saturated with phosphate to the groundwater level.
- If present application rates are maintained, a significant increase of P-saturated soils will occur.

These rather worrisome results suggest that further investigations should be conducted. Because other values of phosphorus sorption capacity do not exist, the data of BREEUWSMA and SCHOUMANS (1987 a,b) were used for further analysis. The aim was to estimate the time scale in which the problem of phosphorus-saturated soils may occur in other agricultural areas. The calculations suggest that serious problems may arise in soils with low phosphorus sorption capacities and high water tables. Perhaps 10 % or more of agricultural areas of the investigated countries belong to this category.

An average depth of the phosphorus saturated zone in a certain year (or the time needed until P-saturation reaches a certain depth) was calculated, assuming a P-sorption capacity of 30 kg P/(ha cm) and an annual accumulation of phosphorus equalling current application rates. In the next 100 years the P-saturation of soils would reach a depth of more than one meter. That means that in all regions with a high water table, phosphorus leaching might occur. The time period needed for leaching is probably even shorter, because the current application methods aim at increasing the phosphorus supply of the upper soil layer, so that more phosphorus may be applied to soils with a low sorption capacity. (Compare regional differences in P-fertilizer application with soil maps).

Characteristic time scales for phosphorus saturation of soils is long, because the inputs to the soil are small compared to the sorption capacities. This implies that in most areas there is still time to study the phenomenon in more detail, and to find preventive measures.

Changing environmental conditions may also affect the phosphorus sorption capacity. For example, changes in *pH* caused by acid rain, and changes in climate are factors which should be considered in this connection.

In general it is assumed that the adsorption of phosphorus does not depend on *pH* because phosphorus can be bound by different ions over a wide range of *pH*. Some authors claim, however, that phosphorus sorption capacity decreases with decreasing *pH* (ANDERSSON, 1987), while others have concluded just the contrary (HARTIKAINEN 1985). The apparent differences in results are very likely due to the different *pH* ranges discussed by the authors. Regarding possible changes of climate, two main processes have to be considered. Firstly, climate may influence yields in a given agricultural area (e.g., higher outputs of phosphorus may reduce the load to the soil). Secondly, changes in precipitation and other parameters of the hydrological cycle are very important, because the phosphorus loading by erosion as well as by phosphate leaching are influenced very strongly by the hydrological cycle.

3.2.2. The nitrogen cycle in agriculture and its consequences

3.2.2.1. Input - output analysis

In contrast to the phosphorus cycle in agriculture, the nitrogen cycle is characterized by strong connections between air, soil and water compartments. An overview of the main processes is given in Figure 6.

Several authors have investigated the nitrogen cycle of agricultural systems, and have tried to estimate the different fluxes (SCHRÖDER, 1985; STEWART et al, 1983; BOSSHART, 1985; KOSHINO, 1975; see also ETCHANCHU and SOUCHU, 1987). Of the nine fluxes comprising the nitrogen cycle, five may in general be estimated on the basis of available data. The difficulty is to quantify the other four to get an estimate of nitrogen leaching. Different authors have obtained quite different results. Therefore, generalization of the results for nitrogen leaching in different countries or regions is not possible. For such an analysis, the same assumptions and sets of parameters have to be used for the different countries or regions.

The magnitude of the difference between nitrogen inputs and yield output and its changes with time were estimated in the same way as for phosphorus. The losses due to volatilization and ammonia emission were included, using the ammonia emission factors for livestock and fertilizer by BUIJSMAN et al (1985). These data were selected because they appear to be the only data suitable for quantifying the process of volatilization with respect to regional differences and changes over time. The emission factors given by BUIJSMAN et al (1985) are based on the total emissions of each source independent of where the emission occurs, so that the method does not distinguish between emissions on the field, during transport or storage, and in livestock sheds.

The results of the input-output analysis are shown in Figures 7 and 8 for Germany, F.R., and G.D.R.. In contrast to the phosphorus cycle, the difference between nitrogen input (fertilizer and manure application minus volatilization) and nitrogen output by crop yield was negative or close to zero up to the end of the 1950s in both countries. Thus, inputs like nitrogen fixation and deposition were required up to this time to produce the recorded yields. In general, the balance between N-input and N-output seems to be positive only when the nitrogen input exceeds about 100 kg N per hectar per year. On this basis it can

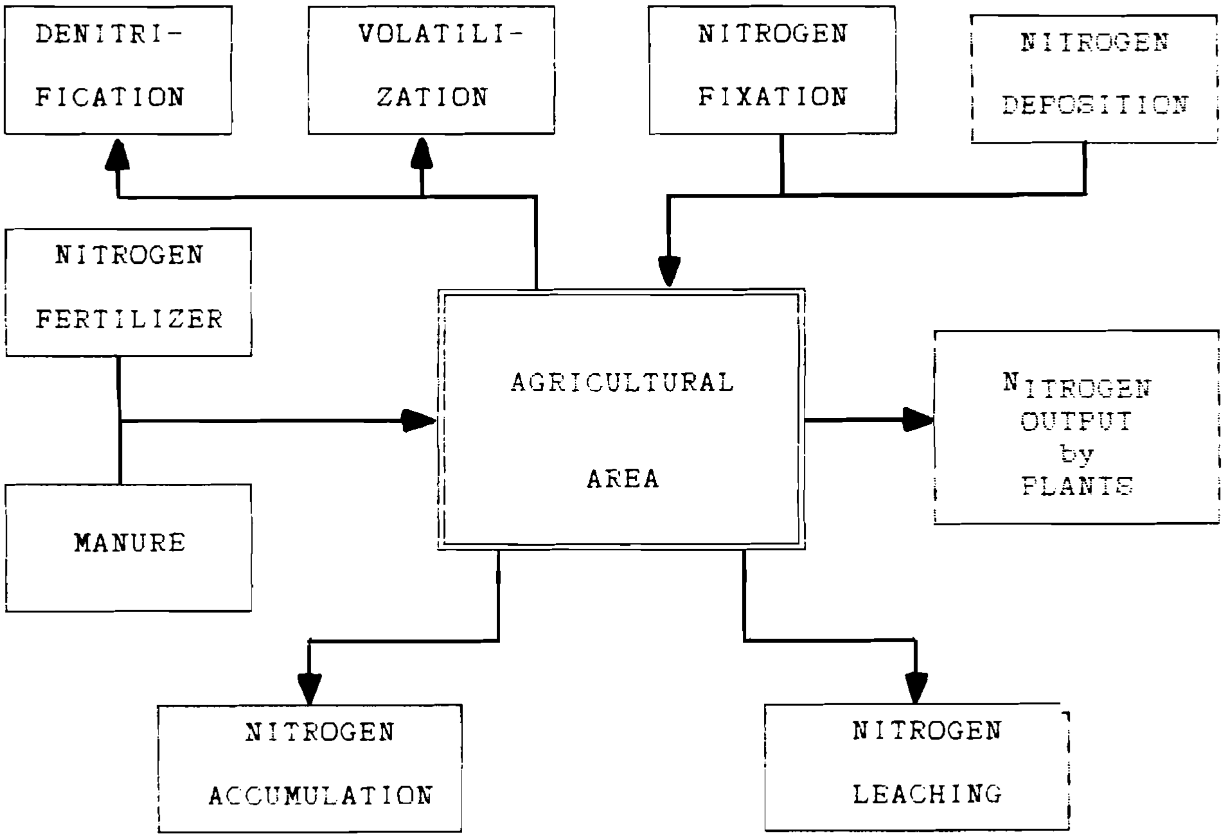

Figure 6: Main processes determining the nitrogen cycle in agricultural areas.

be assumed that significant nitrogen loading into watercourses did not occur before the beginning of the 1960s.

Input-output analysis can be used for a rough approximation of the maximum amount of nitrogen fixation, which is a general problem for an analysis of the nitrogen cycle on such a high level of abstraction. The approximation is based on the relation between the difference in input and output, and the nitrogen input other than from fertilizer and manure. The relations are presented in Figure 9 for all four countries. The regression lines for the two parameters (N-yield and N-input minus output versus N-input intersect the y-axis at about 65 kg N per hectar and year. This intersect may be interpreted as the rate of nitrogen fixation, which occurs on average for all four countries, even if fertilizer and manure are not applied. The same calculations for each country separately show significant differences in the potential N-fixation. In The Netherlands and Denmark it is about 100 kg N/(ha yr), and in Germany, F.R. and G.D.R. it is about 30 kg N/(ha yr). The reasons for these regional differences may be the different climatic conditions, and

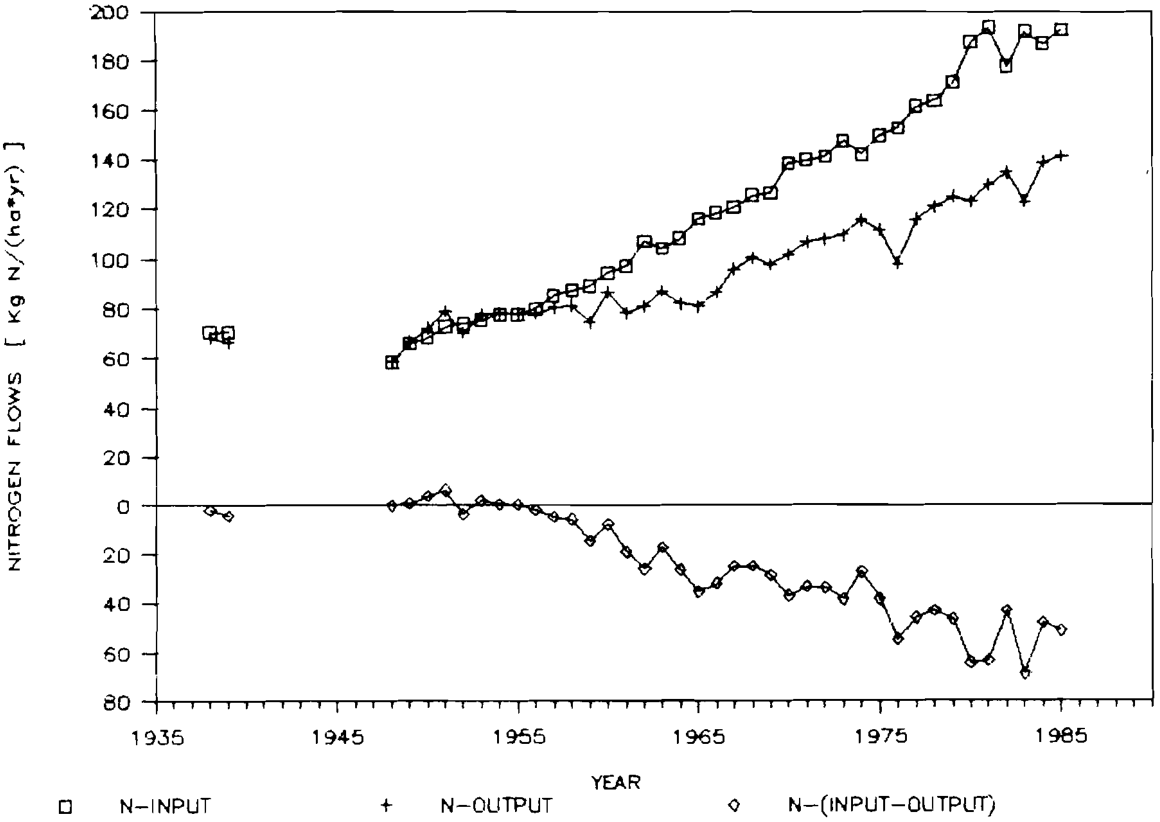

Figure 7: Estimated time trends of nitrogen input by fertilizers and manure, nitrogen output by crops, and the difference between input and output for Germany, F.R. from 1938 to 1985.

differences in the structure of agriculture (for example the relation between cropland and grassland).

For further analysis of the nitrogen cycle, a maximum value of 65 kg N/(ha yr) was assumed for nitrogen fixation. Moreover, a linear decrease in N-fixation with increasing application rates of fertilizer and manure was assumed (see STEWART et al, 1983). The calculated N-fixation approximately agrees with the estimates of SCHRÖDER (1985) for Denmark in the years 1950 and 1980.

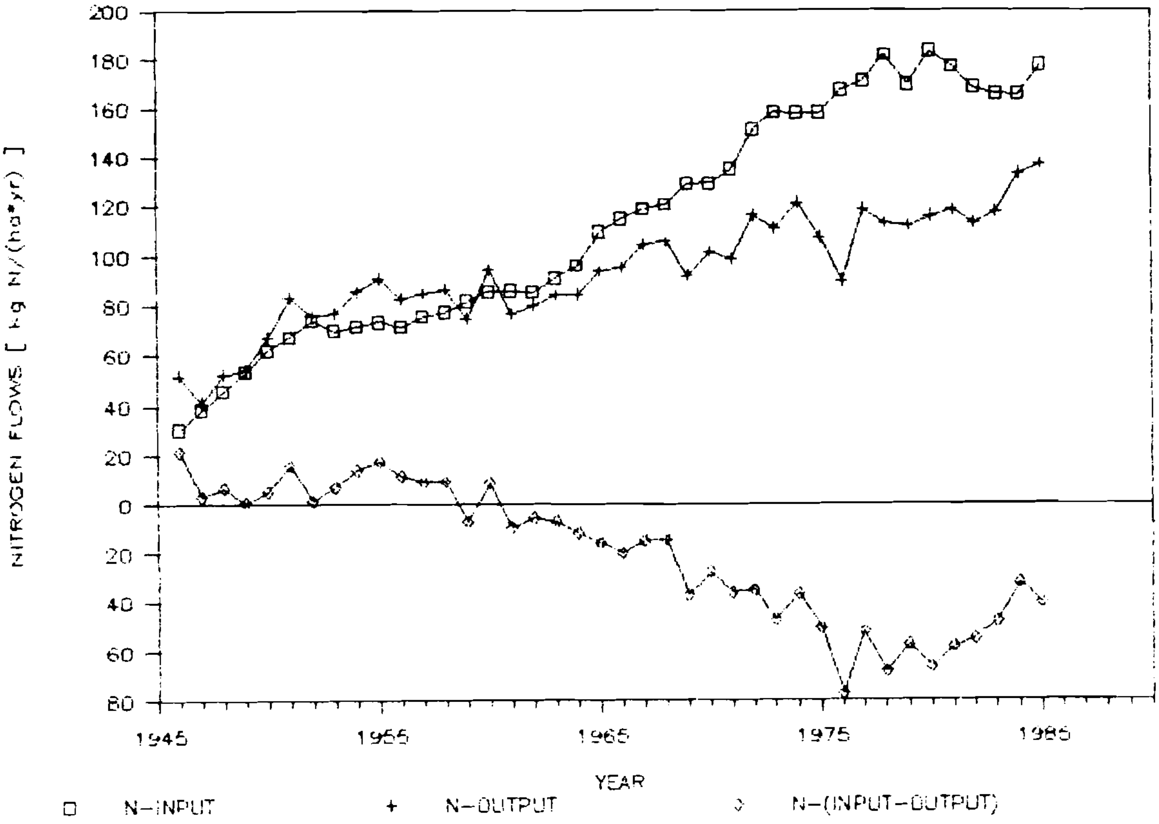

Figure 8: Estimated time trends of nitrogen input by fertilizers and manure, nitrogen output by crops, and the difference between input and output for G.D.R. from 1946 to 1985.

3.2.2.2. Nitrogen loss processes

Six of the nine fluxes of the nitrogen cycle shown in Figure 6 have thus far been estimated. The remaining three are nitrogen accumulation in the soil, denitrification and nitrogen leaching into aquatic ecosystems.

The process of nitrogen accumulation is connected with the question of humus supply in the soil, or more generally with the organic matter content and the rate of mineralization. The comparison between the average nitrogen content of the soil (about 2400 kg N/ha given by SÖDERLUND and SVENSSON (1976) for the upper 1 m) and the total inputs to agricultural areas (200-400 kgN/ ha.yr in the 1970s for the four countries) shows that the capacity of the soil to accumulate nitrogen is more limited than for phosphorus. The time delay for increased nitrogen leaching could be only about ten years. This is in agree-

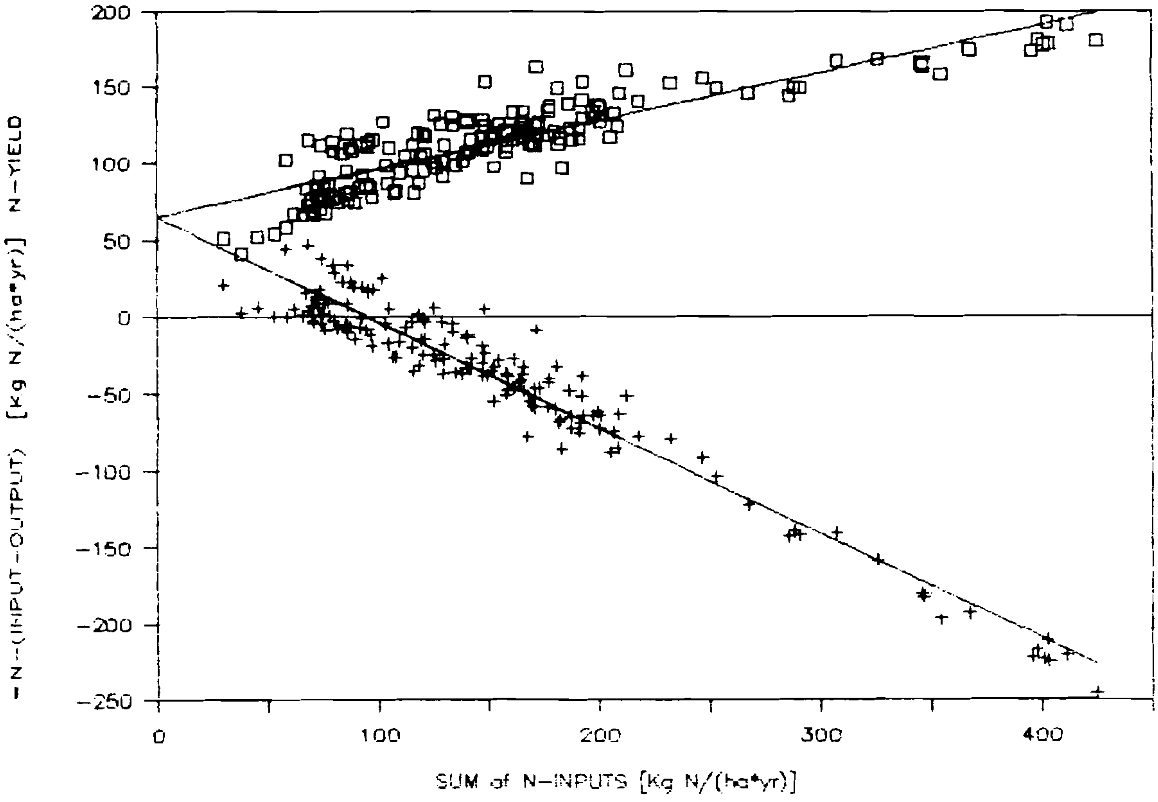

Figure 9: Relationship between nitrogen input by fertilizers and manure, nitrogen output by crops, and the difference between input and output in the agricultural areas of Denmark, Germany, F.R., G.D.R., and The Netherlands during the time period 1945-1985. (n = 156). Regression equations: N - OUTPUT = 65.4 + 0.314 * N - INPUT; r^2=0.762 N - (INP-OUTPUT) = -15.4 + 0.686 * N - INPUT; r^2=0.939

ment with the time delay observed between the beginning of nitrogen overfertilization and the first signs of increased N leaching. Because the net accumulation of nitrogen has to be small at present, this process was neglected in the further analysis.

A separation of the calculated residual losses (denitrification and leaching) is necessary in order to estimate the amount and the trend of potential nitrogen leaching into watercourses. Such a separation is very difficult, because the processes are closely connected. The rate of denitrification is mainly determined by the nitrate content in soil water, temperature and the redox potential. Based on various studies (SCHRÖDER, 1985, STEWART et al, 1983, SÖDERLUND and SVENSSON, 1976, PANNIKOV and MINE-

JEW, 1980, BOSSHART, 1985 and KOSHINO, 1975) the denitrification rate can be assumed to increase linearly with increasing N-inputs, amounting to about 15% of the total nitrogen inputs. On the basis of this assumption, nitrogen leaching from a given agricultural area can be calculated as a difference between all input and output fluxes considered. The results of this calculation are presented in Figure 10. The same behavior as for phosphorus is to be seen for this process too: the potential of nitrogen leaching increases nonlinearly with increasing N-inputs. This behavior corresponds to the qualitative results of several authors (LAWA, 1982; STEWART et al, 1983 and SCHRÖDER, 1985).

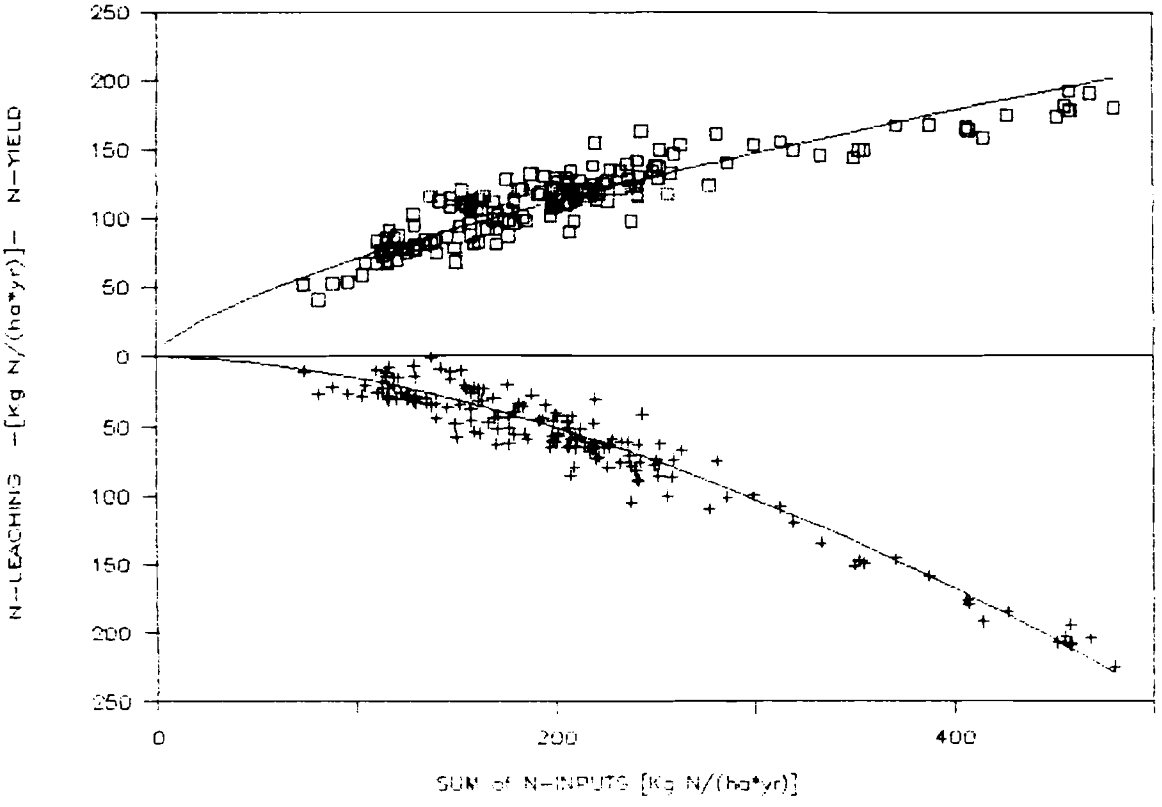

Figure 10: Relationship between the nitrogen input by fertilizers and manure, nitrogen output by crops (N-yields), and nitrogen leaching in the agricultural areas of Denmark, Germany, F.R., G.D.R., and The Netherlands over the time period 1945-1985 (n = 156). Regression equations: LN (N-OUTPUT) = 1.17 + 0.67 * LN (N-INPUT), r^2=0.827; LN (N-LEACHING) = -5.08 + 1.70 * LN (N-INPUT), r^2=0.719

Only part of the leached nitrogen enters the surface waters. According to KOPLAN-DIKS et al (1985), 25% of the total amount of leached nitrogen reaches the surface waters, and the remaining 75 % goes to the groundwaters. Denitrification can still continue on the way from the upper soil layers to the groundwater, resulting in actual N-leaching rates lower than calculated in this paper.

The estimated ratio of nitrogen leaching in the 1960's and around 1980 is about 2.5, which is in a good agreement with the changes in nitrate concentration observed in the Baltic Sea for the same period of time. NEHRING (1985) estimated a ratio of 2.4 based on measurements in different parts of the Baltic Sea. A similar increase of nitrate concentration with time was described by PROCHASKOWA and BLAZKA (1986) for, Czechoslovakian rivers, by BENNEKOM and SALOMONS (1981) for the river Rhine and by ETCHANCHU and SOUCHU (1987) for French rivers.

Consequences of increased nitrate leaching are contaminated drinking water supplies and eutrophication of aquatic ecosystems. These problems have already been observed since the 1970s. Therefore, efforts were undertaken in all countries investigated to stop the increase of nitrogen inputs. In connection with increasing agricultural yields, a slightly decreasing trend in nitrogen leaching has been observed in G.D.R., where the nitrogen inputs are smaller than in the other three countries.

Because nitrogen leaching and other processes in the nitrogen cycle are closely connected with hydrology, the cycle is expected to be highly sensitive to possible changes of climate. However, quantitative predictions regarding changes in the amount of nitrogen leached have not been made.

According to current knowledge of the processes determining the nitrogen cycle, decreasing rates of nitrogen leaching are guaranteed by a further increase in crop yields together with constant or decreasing N-inputs. A significant reduction in nitrogen leaching might be possible in the future assuming the implementation of new technologies, which might affect greatly such processes as N-fixation and denitrification.

3.3. Nutrient losses from forest areas

Regarding forest ecosystems and nutrient loading into watercourses, a similar detailed analysis was not possible due to time limitations and insufficient data bases.

Therefore, only a summary of the results of other authors is given of the nutrient balance and the various components of nutrient cycles for forest ecosystems.

FIEDLER et al (1985) presented a detailed quantitative overview on the phosphorus balance processes in forested watersheds. At present the phosphorus cycle of forest ecosystems is well-balanced. The P-inputs from deposition and weathering roughly equal the P-outputs by yield and phosphorus losses into water courses. Only whole tree harvesting leads to phosphorus impoverishment of the soil.

On this basis, changes in land use from agriculture to forestry might be advantageous for soils vulnerable to phosphate leaching.

The average P-output from forested areas into water courses is on the order of about 0.1 kg TP/ ha.yr, ranging from 0.03 to 0.25 kg P/ ha.yr. An increase in phosphorus leaching is proposed by ANDERSSON (1986) in connection with acidification. But due to the small difference between P-input and P-output by trees, phosphorus leaching will increase significantly only if phosphorus deposition increases as well, or if the uptake by trees decreases as a result of direct effects of acidification on forests.

While phosphorus seems to be well-balanced in forested ecosystems, the nitrogen budget is characterized more and more by a surplus of nitrogen inputs (deposition) compared to the output by plants. In the past, the N-inputs into forests by deposition were small in comparison to the total nitrogen content of the soil, and the increase of nitrogen deposition was compensated by increased tree growth (ANDERSEN, 1987 and DICKSON, 1987). However, if the current accumulation of nitrogen in forested ecosystems continues, a saturation point will be reached resulting in increased leaching of nitrogen (DICKSON, 1987).

4. Not-impossible future changes in nonpoint nutrient loading from agricultural areas

On the basis of the analysis of the four countries, the environmental consequences caused by different possible future changes in agriculture and land use can be assessed. In this Section, the not-impossible changes associated with the currently discussed strategies of agriculture will be evaluated. Three general, quite different scenarios for the development of agriculture are discussed: continuation of the present trend, separation of agricultural and natural systems, and integration of agricultural and natural systems.

1. *Continuation*

   This scenario is based on a continuation of current trends in agricultural productivity. Agricultural activity is focused on increasing the yield by increasing labor productivity. Because a significant overproduction already exists in Western Europe and in G.D.R., the surpluses must be exported.

2. *Separation*

   The outlook for the further separation of the different ecosystems is based on the idea that agriculture and environment might be best served by physical separation. In this way both interests could be optimally served in their own right and by their own means (de WIT et al., 1987). The basic assumption of this perspective is that significant increases in yield are still possible, so that all demands of agriculture can be met with greater efficiency on a smaller area than at present. Because the total output from the agricultural sector should be constant in the future, designated areas must be phased out of agricultural production. These might be transformed to forest or other nature reserves.

3. *Integration*

   The concept of integration assumes that agriculture and environment are mutually interdependent, and that both interests are best served by spatial intervention and integration of their functions (de WIT et al., 1987). From this perspective, present day agriculture is too much concentrated on increasing labor productivity and yield at the expense of the productivity of soil, energy consumption, and other basic resources, as for example nutrients.

Each of these scenarios may be associated with certain advantages and disadvantages, depending on one's point of view and time frame. But from the environmental perspective, the third scenario is preferred. All four countries investigated in this report have attained an agricultural productivity level such that food self-sufficiency is secure. Currently this level must be regarded as the upper limit to which deleterious influences on the environment can be tolerated. Our analysis has shown that the relationships of nitrate leaching and of phosphorus accumulation in the soil to the agricultural inputs have been strongly nonlinear in the past and present. (See Figures 4 and 10). This implies that the first two scenarios would lead to even larger increases of nutrient losses to the environment in the future.

Exceptions might be the so-called marginal areas, where no intensive agriculture would exist in the separation scenario. A quantitative example can be used to elucidate the effects of the different strategies on the nutrient load. Assume that currently a given watershed is used for agricultural purposes only. Assume also that although an increase in yield per hectar is possible, the total yield remains constant, by taking some of the land out of agricultural production and converting it to forest. Assume further that yield has increased by 50 %, and that 33 % of the area has been converted to forest to maintain a constant total yield. Using the correlations of nutrient inputs and outputs in agriculture to inputs and losses to soil and water (Figures 4 and 10), the following results are obtained:

> Total nitrogen leaching and phosphorus accumulation in the soil increase by about 20 - 30 % for the whole area, excluding the losses from the new forested areas. Although one third of the agricultural area is converted to forest, the nutrient losses from the two thirds remaining in agricultural use increase so strongly (by more than 100%), that the total losses from the whole area are higher than before. The reason is the decreasing nutrient utilization rate with increasing yield as the result of higher inputs of fertilizers and manure.

Nutrient losses would not increase further only if nutrient utilization were to increase by an amount that compensated for the increased inputs. Assuming that nutrient utilization could increase by about 10% under the condition that yield and land for agricultural production remain constant, less inputs of fertilizer would be required and losses to soils and water could decrease by up to 30%. This situation could be realized only in the integrated system. At the same time, a better utilization is of course advantageous from the economic point of view.

This example illustrates that introducing integrated agriculture into practice could substantially reduce environmental risks, and that in general, more effort should be undertaken in agriculture to increase nutrient utilization.

5. CONCLUSIONS

This study is merely the first step in the analysis of potential environmental problems stemming from agricultural inputs of major nutrients. Although the results are preliminary, three important conclusions can be made:

- The problem of nutrient loading (nitrogen and phosphorus) into water courses is not only a problem of our century, but also of the next if we are not able to solve the problems of increasing nutrient deposition and the poor utilization of nutrients in agriculture. Especially in the case of phosphorus inputs, accumulation in soils may result in deleterious effects that may be manifested only in the next century.

- Both input-output analysis and mass balance calculations are suitable for investigating leaching and accumulations of nutrients into the environment from nonpoint sources, and for estimating historical changes and projecting into the future. The analysis can be extended to other substances with a minimum of effort, because the analytical procedure was designed such that only substance-specific parameters and processes need to be changed. The relationship between the inputs and the carrying capacity of different environments enables us to determine the time scale over which effects might occur.
- More interdisciplinary and international research is needed regarding nutrient loadings into water courses, because the associated problems are so closely connected with complex socio-economic questions, and occur on spatial scales that do not respect national boundaries. Thus, investigations should be extended to cover a greater time horizon in the past, and a larger spatial scale than that of the four countries investigated in this paper. On the other hand, more detailed, process-oriented models are needed on reduced spatial scales in order to quantify more accurately some of the processes comprising the major nutrient cycles. Point sources and their changes in the past and future should be taken into account as well.

REFERENCES

Ahl, T. (1979): Natural and human effects on trophic evolution. Arch. Hydrobiol. Beih. Ergebn. d. Limnol. 13, 259-277.

Andersen, B. (1987): Impact of nitrogen deposition. In: NILSSON.J.(Ed.) *Critical loads for sulphur and nitrogen.* Report from a Nordic group, 161-197.

Andersson, F. (1986): Acidic Deposition and its effects on the forests of Nordic Europe. *Water, Air and Soil Pollution 30,* 17-29.

Anonymous (1987): Land-sea boundary flux of pollutants. Final report of working group 22, Joint Group of Experts on the Scientific Aspects of Marine Pollution, 17th Session, 30 March - 3 April 1987, 225 p.

Anonymous (1985): Report of the international conference on the Assessment of the role of carbon dioxide and the other greenhouse gases in climate variations and associated impacts. Villach, Austria, 9-15 October 1985.

Asman, W.A.H. (1986): A long range transport model for ammonia and ammonium for Europe and some model experiments. IMOU - Report R-86-6, 75 p.

Ayres, R.U. and Rod, S.R. (1986): Patterns of Pollution in the Hudson-Raritan basin. *Environment 28, 4, 14-20 39-43.*

Babenerd, B. and Zeitzschel, B. (1985): Trends für eintrags- relevante Faktoren und für die Nährstoffkonzentrationen im Wasser der Kieler Bucht. Berichte aus dem Institut für Meereskunde der Universität Kiel 148, 45 p.

Bennekom van, A.J. and Salomons, W. (1981): Pathways of nutrients and organic matter from land to ocean trough rivers. In: *River Inputs to Ocean Systems.* Proceedings of a Review Workshop held at FAO, Rome, 26 to 30. March 1979. United Nations, New York, 33-51.

Bernhardt, H. (1978): Phosphor - Wege und Verbleib in der BRD. Verlag Chemie, Weinheim.

Bosshart, U. (1985): Einfluss der Stickstoffdüngung und der landwirtschaftlichen Bewirtschaftungsweise auf die Nitratauswaschung ins Grundwasser. Beiträge zur Geologie der Schweiz - Hydrologie 32, 107 p.

Breeuwsma, A. and Schoumans, O.F. (1987a): Forecasting the impact of environmental legislation on leaching of phosphate and nitrate from agricultural soils. Proceedings of the EC- workshop on Aspects of the Impact of Agriculture on the Environment, Copenhagen, Denmark, October 1986.

Breeuwsma, A. and Schoumans, O.F. (1987 b): Forecasting phosphate leaching from soils on a regional scale. Proceedings of the Conference on Vulnerability of Soil and Groundwater to pollutants (VSGP), Noordwijk aan Zee, The Netherlands.

Buijsman, E., Maas, J.F.M. and Asman, W.A.H. (1985): Ammonia emission in Europe. IMOU Report R-85-2, 26 p.

Dickson, W. (1987): Critical loads for nitrogen on surface waters. In: NILSSON, J. (Ed.) *Critical loads for sulphur and nitrogen.* Report from a Nordic working group, 200-212.

Drecht van, G. (1987): Modeling of nitrate leaching in the Dutch sandy areas. Proceedings of the Conference on Vulnerability of Soil and Groundwater to Pollutants (VSGP), Noordwijk aan Zee, The Netherlands.

Ernst, W.H.O. and Joosse-van Damme, E.N.G. (1983): Umweltbelastung durch Mineralstoffe. VEB Gustav Fischer Verlag Jena, 234 p.

Fiedler, H.J., Katzschner, W. and Richter, B. (1985): Phosphor in bewaldeten Wassereinzugsgebieten. II. Quantitative Kennziffern. Wissenschaftliche Zeitschrift der Technischen Universität Dresden 34, 4, 217-224.

Goulding, K.W., Poulton, P.R., Thomas, V.H. and Williams, R.J.B. (1986): Atmospheric deposition at Rothamsted, Saxmundham, and Woburn experimental stations, England, 1969-1984. *Water, Air and Soil Pollution 29, 27-49.*

Hamm, A. (1976): Zur Nährstoffbelastung von Gewässern aus diffusen Quellen: Flächenbezogene P-Abgaben - Eine Ergebnis- und Literaturzusammenstellung. Z. f. Wasser- und Abwasser- Forschung 9, 1, 4-10.

Koplan-Diks, I.S., Nasarow, G.W. and Kusnezow, W.K. (1985): Role of mineral fertilizer on eutrophication of freshwater. Nauka Publisher, Leningrad, 184 p. (in Russian).

Koshino, M. (1975): Incoming and outcoming of fertilizer in cropped lands. In: *Science for better environment.* Proceedings of the International Congress on the Human Environment (HESC) Kyoto 1975. Pergamon Press Oxford, New York, 206-214.

Larsson, U., Elmgren, R. and Wulff, F. (1985): Eutrophication and the Baltic Sea: Causes and consequences. *Ambio 14, 1, 9-14.*

Lawa - Landerarbeirsgemeinschaft Wasser - (1982): Einflüsse von Düngern auf die Gewässergüte. 60 p.

Nehring, D. (1985): Langzeitänderungen essentieller Nährstoffe in der zentralen Ostsee. *Acta hydrochim. hydrobiol.* 13, 5,591-609.

Novotny, V. and Chesters, G. (1981): Handbook of nonpoint pollution. *Sources and management.* Van Nostrand Reinhold Company, New York, London, Melbourne, 555 pp.

Pannikow, W.D. and Minejew, W.G. (1980): Boden, Klima, Düngung und Ertrag. VEB Deutscher Landwirtschaftsverlag Berlin, 423 p.

Peskin, H.M. (1986): Cropland Sources of water pollution. *Environment 28, 4, 30-34 44.*

Pierrou, U. (1976): The global phosphorus cycle. In: SVENSSON, B.H. and SÖDERLUND, R. (Eds.). *Nitrogen, Phosphorus and Sulphur - Global Cycles.* SCOPE Report 7, 75-88.

Prochazkova, L. and Blazka, P. (1986): Long-term Trends in Water Chemistry in the Vltava River (Czechoslovakia). *Limnologica* 17, 2, 263-271.

Rigler, F.H. (1974): Phosphorus cycling in lakes. - In: RUTTNER, F. (Ed.) *Fundamentals of Limnology*, University of Toronto Press, Toronto, pp. 263-273.

Runge, P. and Matzel, W. (1985): Die Entwicklung von Düngemittelaufwand und Sortiment in der DDR. Int. Z. Landwirtschaft 2, 150-152.

Schoumans, O.F., Breeuwsma, A. and de Vries, W. (1987): Use of soil information for the assessing the phosphate sorption capacity of heavily manured soils. Proceedings of the International Conference on the Vulnerability of Soil and Groundwater to Pollutants (VSGP). Noordwijk aan Zee, The Netherlands.

Schröder, H. (1985): Nitrogen losses from Danish agriculture - trends and consequences. *Agriculture, Ecosystems and Environment 14, 279-289.*

Söderlund, R. and Svensson, B.H. (1976): The global nitrogen cycle. In: SVENSSON,B.H. and SÖDERLUND, R. (Eds.). *Nitrogen, Phosphorus and Sulphur - Global cycles.* SCOPE Report 7, 23-74.

Statistical Yearbook of The Netherlands 1950 -1986.

Statistical Yearbook of Denmark 1950 -1985.

Statistische Jahrbücher der DDR 1949 -1986.

Statistische Jahrbücher der BRD 1950 - 1986.

Stewart, W.D.P., Gasser, J.K.R., Holding, A.J. et al (1983): The nitrogen cycle of the United Kingdom. A study group report. The Royal Society, London, 264 pp.

Stigliani, W., Clark, W. and Hordijk, L. (1987): Future environments for Europe: The implications of alternative development paths. A study of IIASA's projects on ecologically sustainable development of the biosphere and acid rain. Draft version, 25 pp.

Vollenweider, R.A. and Dillon, P.J. (1974): The application of the phosphorus loading concept to eutrophication research. National Research Council of Canada, Environmental Secretariat, Publication No. NRCC 13690, 42 p.

Wagner, G. and Wohland, H. (1976): Simulationsmodelle der Seen- eutrophierung, dargestellt am Beispiel des Bodensee- Obersees. Teil I.: Die in den Simulationsmodellen verwendeten Daten vom Bodensee-Obersee. *Arch.Hydrobiol.* 77, 4,431-457.

Wagner, G. and Wohland, H. (1976): Simulationsmodelle der Seen- eutrophierung, dargestellt am Beispiel des Bodensee- Obersees. Teil II.: Simulation des Phosphorhaushaltes des Bodensee-Obersees. *Arch.Hydrobiol.* 78, 1, 1-41.

Wazer van, J.R. (1961): Phosphorus and its compounds, Vol. 2. . Interscience Publishers Inc., New York and London, 1091 pp.

Wit de, C.T., Huisman, H. and Rabbinge, R. (1987): Agriculture and its environment: Are there other ways? *Agricultural Systems 23, 211-236.*